

SUB-PIXEL RESPONSE MEASUREMENT OF NEAR-INFRARED SENSORS

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ABSTRACT

Wide-field survey instruments are used to efficiently observe large regions of the sky. To achieve the necessary field of view, and to provide a higher signal-to-noise ratio for faint sources, many modern instruments are undersampled. However, precision photometry with undersampled imagers requires a detailed understanding of the sensitivity variations on a scale much smaller than a pixel. To address this, a near-infrared spot projection system has been developed to precisely characterize near-infrared focal plane arrays and to study the effect of sub-pixel non uniformity on precision photometry. Measurements of large format near-infrared detectors demonstrate the power of this system for understanding sub-pixel response.

Subject headings: cosmology – photometry – astronomical instrumentation

1. INTRODUCTION

The *Hubble Space Telescope* (HST) has provided overwhelming evidence for the power of a space-based platform for optical and near-infrared (NIR) astronomical observations (Williams et al. 1996). In particular, access to diffraction limited imaging, stable observing conditions, and low background levels have revolutionized our understanding of the faint and distant universe.

Space-science instruments are evolving from the initial HST instruments that provided narrow-field observations to large scale survey instruments capable of providing HST quality (or better) data across large regions of the sky. The HST began this trend toward large-scale surveys with the Advanced Camera for Surveys (ACS) in 2002 (Golimowski et al. 2002). The ACS has enabled a series of relatively wide-field surveys, such as the GOODS, GEMS, and COSMOS surveys, however even the largest of these reaches only a few square degrees. These surveys provide deep, high-resolution imaging, but a limited picture of the statistical properties of the objects they detect, and little information about the large scale distribution of these objects. For comparison, large ground based surveys, such as the SDSS (10,000 square degrees) provide precise statistical information with lower resolution. (Gunn et al. 1998)

Future space-science instruments will combine high-resolution with wide-field imaging to provide new data sets for cosmology and astrophysics. Wide-field imaging missions have been proposed to study such diverse topics as planets (Kepler) (Borucki et al. 2003), microlensing (GEST) (Bennett and Rhie 2002), and dark energy (e.g. SNAP (Aldering et al. 2004) and DESTINY (Benford and Lauer 2006)). The central science goals for most of these missions depend on the ability to make precise photometric measurements in imaging mode. For example, Kepler will monitor the brightness of about 10^5 stars, watching for the very slight dimming ($< 1\%$) associated with planetary transits. SNAP will achieve relative dis-

tance measurements with a smaller than 2% uncertainty by comparing the restframe B and V magnitudes of type Ia supernovae.

To achieve wide-field imaging and high resolution at an affordable cost, many modern instruments operate in a critically sampled, or undersampled mode. Such observations require a detailed understanding of the detector response. Large scale inter-pixel variations in detector response are characterized by a variety of well established flat-fielding methods. However, no such methods exist for small scale intra-pixel sensitivity variations, which introduce uncertainties in the conversion between the detected signal and incident light.

2. INSTRUMENT

To study the intra-pixel response in NIR sensors, an automated spot projection system has been developed. This system, the “Spot-o-Matic,” is part of the University of Michigan Near Infrared Detector Testing Facility. It is designed to measure one-dimensional and two-dimensional sub-pixel response profiles in large format NIR focal plane arrays (FPAs) which are used in wide-field surveys. Typical pixel sizes⁴ for such detectors are approximately $20 \times 20 \mu\text{m}^2$. The Spot-o-Matic performs sub-pixel response measurements by step-scanning a stable, micron-sized spot across a small region of the detector, and recording the detector’s response at each spot position. A computer controlled x - y - z stage allows for large high-resolution step-scans of 25 to 50 pixels with sub-micron motion control. As intra-pixel sensitivity variations were expected to be at the few percent level, the system was designed to achieve a relative accuracy of better than 1%. The Spot-o-Matic has achieved this accuracy goal in measuring the pixel response function (PRF) for the commercially-produced large format NIR sensors listed in Table 1.

2.1. Overview of Technique

The design for the Spot-o-Matic is based on the concept of a pinhole projector for visible light that was developed to measure diffusion in Charge Coupled Devices (CCDs) (Wagner 2002). This concept has been extended

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⁴ Pixel sizes as small as $9 \times 9 \mu\text{m}^2$ are now under development.

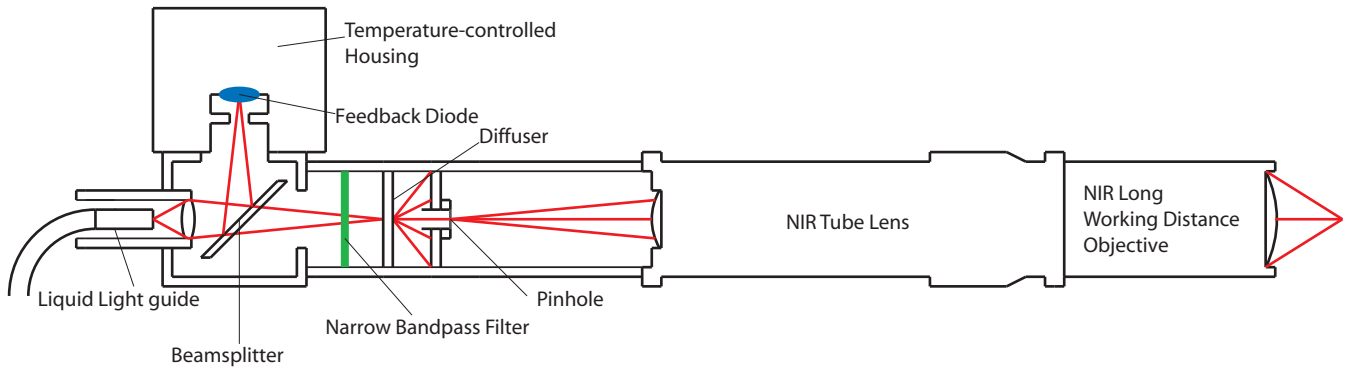


FIG. 1.— Schematic diagram of the optical components of the Spot-o-Matic.

to an instrument that operates both at visible and NIR wavelengths. The principle optical components of the instrument are outlined in Fig. 1.

NIR detectors designed for low background applications must be cooled to limit the generation of thermal carriers (dark current) to acceptable values. Therefore, the Spot-o-Matic utilizes a long working distance objective to project a spot onto a NIR detector which is mounted inside a cryogenic dewar (not shown in the figure). The Spot-o-Matic light source is a 50W QTH (quartz-tungsten-halogen) lamp (Ushio BRL 12V50W) powered by a Spectra Physics power supply (Model No. 69931) and operated in constant current mode. This mode of operation provides better than 1% stability and ensures that light intensity variations are accurately decoupled from any detector response variations.

The lamp is enclosed in a Photomax housing (Spectra Physics Model No. 60100) with an elliptical reflector that focuses the light into a liquid light guide.⁵ This guide directs the light into an optical assembly, where it is divided by a 30/70 beam splitter (see Fig. 1). The weaker beam is directed to a silicon feedback diode, while the stronger beam passes first through a narrow bandpass filter and then through a diffuser before it illuminates the pinhole. Light passing through the pinhole travels through a NIR tube lens before it is focused by a long working distance NIR microscope objective, through the dewar window, onto a cold sensor (not shown in Fig. 1). The demagnification of the pinhole image is set by the distance of the pinhole from the microscope objective. The results presented here use a $10\text{ }\mu\text{m}$ pinhole and a $20\times$ demagnification. With this configuration, the spot point spread function (PSF) is nearly diffraction limited at wavelengths above 1000 nm .

The focusing microscope objective is a Mitutoyo infinity-corrected long working distance objective,⁶ chromatically corrected from 480 nm to 1800 nm for both NIR and visible operation. Spot sizes as small as $\sigma = 1\text{ }\mu\text{m}$ have been achieved at a wavelength of 1050 nm . Spot sizes above the diffraction limit can be produced by varying the pinhole aperture and the demagnification. A set of narrow-bandpass filters (10 nm FWHM) allows for stable near-monochromatic sampling of the spectral sensi-

tivity range of the tested detectors.

The Spot-o-Matic optics are mounted on an NAI (National Aperture Inc.) Extended Motorized MicroMini Stage (Model No. MM-4M-EX-80) which supports high-precision, high-resolution x - y - z motion control.⁷ The x and y axes have a minimum step size of $0.075\text{ }\mu\text{m}$, with a positioning error of less than $1\text{ }\mu\text{m}$ per 2.54 cm of linear travel, and a repeatability of $\pm 0.5\text{ }\mu\text{m}$. To ensure a reproducible focus, the z axis uses a high-resolution linear encoder with a step size of 20 nm . This provides an accurate reading of the stage position, and avoids gear-head backlash when changing the direction of travel. The stage is controlled by an NAI Motion MC-4SA Servo Amplifier System. Custom LabView interfaces automate the test procedures.

The Spot-o-Matic assembly is mounted on an optical table inside a dark enclosure to reduce the background photon flux. The tested sensors have a cutoff wavelength between 1550 nm and 1750 nm and are thus sensitive to a large background (a few thousand photons/pixel/second) of thermal radiation from the optics and the walls of the dark enclosure at room temperature (297 K). To reduce the thermal photon background, an effort was made to place a cold narrow-band filter inside the dewar; however, due to space constraints a filter could not be accommodated. Thus the intensity of the projected spot was raised to a level at which the measurement was no longer dominated by thermal radiation. For typical spot intensities and room temperature background fluxes, the statistical uncertainty limit due to shot noise on the source plus background photons is less than 1%.

2.2. Beam Spot Characterization

In order to measure intra-pixel responses, the Spot-o-Matic is designed to produce spots much smaller than typical NIR pixels. For the measurements reported here, scans were performed at wavelengths of 1050 nm and 1550 nm . These two wavelengths were chosen to probe both the short and long wavelength response of the detectors. 1550 nm was chosen because the long wavelength cutoff of the InGaAs detector, which is $1.7\text{ }\mu\text{m}$ at room temperature, drops to $1.6\text{ }\mu\text{m}$ at 140 K due to an increased bandgap energy at lower temperatures. 1050 nm is near the approximately 850 nm cutoff of those detectors that do not have the substrate removed.

⁵ Traditional fiber optics absorb light in the NIR, but liquid light guides have high transmission through both the optical and NIR spectrum.

⁶ The working distance is 31 mm , with a numerical aperture (NA) of 0.26

⁷ The z axis is the focus axis, x and y scan the projected spot across detector the detector's columns and rows.

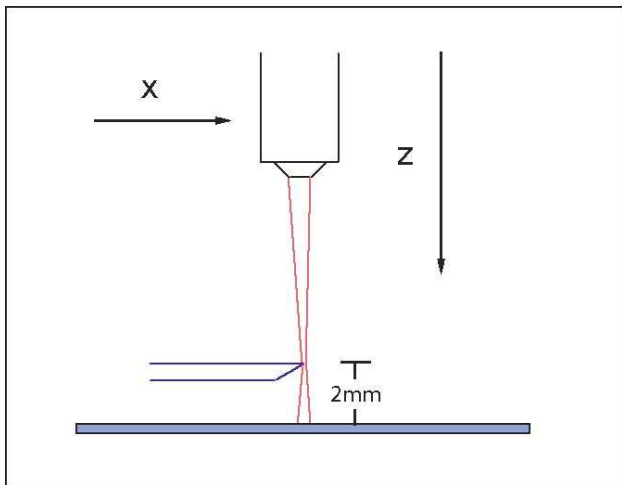


FIG. 2.— Schematic diagram of the Foucault knife-edge scanning procedure. The point source image is scanned across a precision edge in the x direction to determine the line spread function. The image location is found by focusing the beam in the z direction to minimize the spot size. The unobscured beam typically extends over a few hundred pixels

The beam profile is measured using the Foucault knife-edge technique, a procedure commonly used to determine the spatial profiles of images from point sources (Firester et al. 1976). The transmitted beam intensity is recorded as a spot is stepped across a razor blade mounted 2 mm above the detector surface, as shown in Fig. 2. Since the unobscured beam covers a few hundred pixels, sensitivity variations within pixels do not affect the measurement.

Figure 3 shows the results from a series of knife-edge scans performed at wavelengths of 1050 nm and 1550 nm. The top panels in this figure show the transmitted light intensities, or edge traces, as a function of the beam's horizontal position. The bottom panels in Fig. 3 show the spatial profiles, or line spread functions (LSFs), obtained by differentiating the edge traces. Note the small “shoulder” on the left side of each LSF. This shoulder likely results from stray light reflected off the razor blade.

A Gaussian function⁸ provides an excellent fit to the central spot profile, as shown in Fig. 3 (the bottom panels). At a wavelength of 1050 nm, the LSF has a fitted width of $\sigma = 0.95 \pm 0.03 \mu\text{m}$, while at 1550 nm the width has increased to $\sigma = 1.28 \pm 0.04 \mu\text{m}$.

The expected widths of each LSF can be calculated by convolving the Airy disk with the demagnified geometric pinhole image. The full width at half maximum (FWHM) of the Airy disk is given by

$$\text{FWHM} = 1.03 \lambda \frac{\sqrt{1 - \text{NA}^2}}{2 \text{NA}}, \quad (1)$$

where the numerical aperture, NA, is 0.26 for the Spot-o-Matic optics. The root mean squared (rms) width of a circular spot is $\sigma = 0.82 d$, where $d = 0.5 \mu\text{m}$ is the diameter of the demagnified pinhole image in the absence of diffraction. Adding the two components in quadrature yields an expected spot size of $0.94 \mu\text{m}$ at a wavelength of 1050 nm and $1.32 \mu\text{m}$ at 1550 nm. These predictions are in excellent agreement with the measured values.

⁸ A correct description of the spot profile is the one-dimensional integral of a two-dimensional Airy disk convolved with the demagnified geometric pinhole image; however, the Gaussian function provides a sufficiently good approximation.

2.3. Pixel Response

To focus the spot onto the detector surface, a virtual knife-edge procedure is employed. This method is analogous to the Foucault knife-edge procedure, but does not use a razor blade to obstruct the beam. Instead, a sub-pixel size spot is step-scanned across the center of an individual pixel while the signal in that pixel is recorded. The edge of the pixel serves as the edge of the razor blade in the Foucault knife-edge scan, and best focus is achieved at minimum edge width. Although diffusion between pixels widens the edge, it remains constant and is independent of the spot size.

Figure 4 shows the intensity profile for a single representative pixel and its derivative at a wavelength of 1050 nm. The measured intensity profile shown in the upper panel reflects the convolution of the Spot-o-Matic PSF and the pixel response function, the latter of which includes contributions from lateral charge diffusion as well as capacitive coupling between neighboring pixels. Capacitive coupling is a deterministic process by which pixels share charge after photon collection. This is in contrast to charge diffusion which occurs prior to charge collection (Moore et al. 2004; Brown et al. 2006) and is stochastic.

Once the best focus is established, a small region of pixels (approximately 6×6 pixels) is step-scanned in two dimensions to measure pixel response. The spot is scanned repeatedly across the detector in the x direction with incremental steps of $1 \mu\text{m}$ to $2 \mu\text{m}$ in the y direction between scans. The detector response is recorded at each spot position to produce detailed two-dimensional pixel response profiles.

The measured single pixel response shown in Fig. 5 is nearly symmetric. Lateral charge diffusion, capacitive coupling, as well as a contribution from the higher order rings of the Airy disk produce a signal in the measured pixel even when the spot is projected onto a neighbor pixel. Diffraction accounts for only a small portion of the signal measured outside the illuminated pixel: when a spot (with a wavelength of 1050 nm) is centered in a pixel, approximately 2% of the light is diffracted onto the eight surrounding pixels. Almost all of the signal measured outside the illuminated pixel is due to charge diffusion and capacitive coupling between the pixels. Charge diffusion increases the edge transition's rms width to $\sigma = 2.6 \mu\text{m}$, compared to $\sigma = 0.95 \mu\text{m}$ obtained from the Foucault knife-edge scan.

Extraction of the PRF requires unfolding of the measured pixel response from the measured point spread function of the projected spot (see Section 3.2).

3. RESULTS AND ANALYSIS

The pixel scan data is analyzed in several ways. First, the data from adjacent pixels is summed to identify dips in sensitivity between those pixels. The spot PSF is then removed so that diffusion and capacitive coupling can be measured. Next, the full two-dimensional scans are summed over an 8×8 region of pixels to investigate the integrated response as a function of PSF centroid position.

The Spot-o-Matic was used to test five detectors (see Table 1). All detectors were produced as part of an ongoing research and development program (Schubnell et al. 2006) and different performance characteristics were tar-

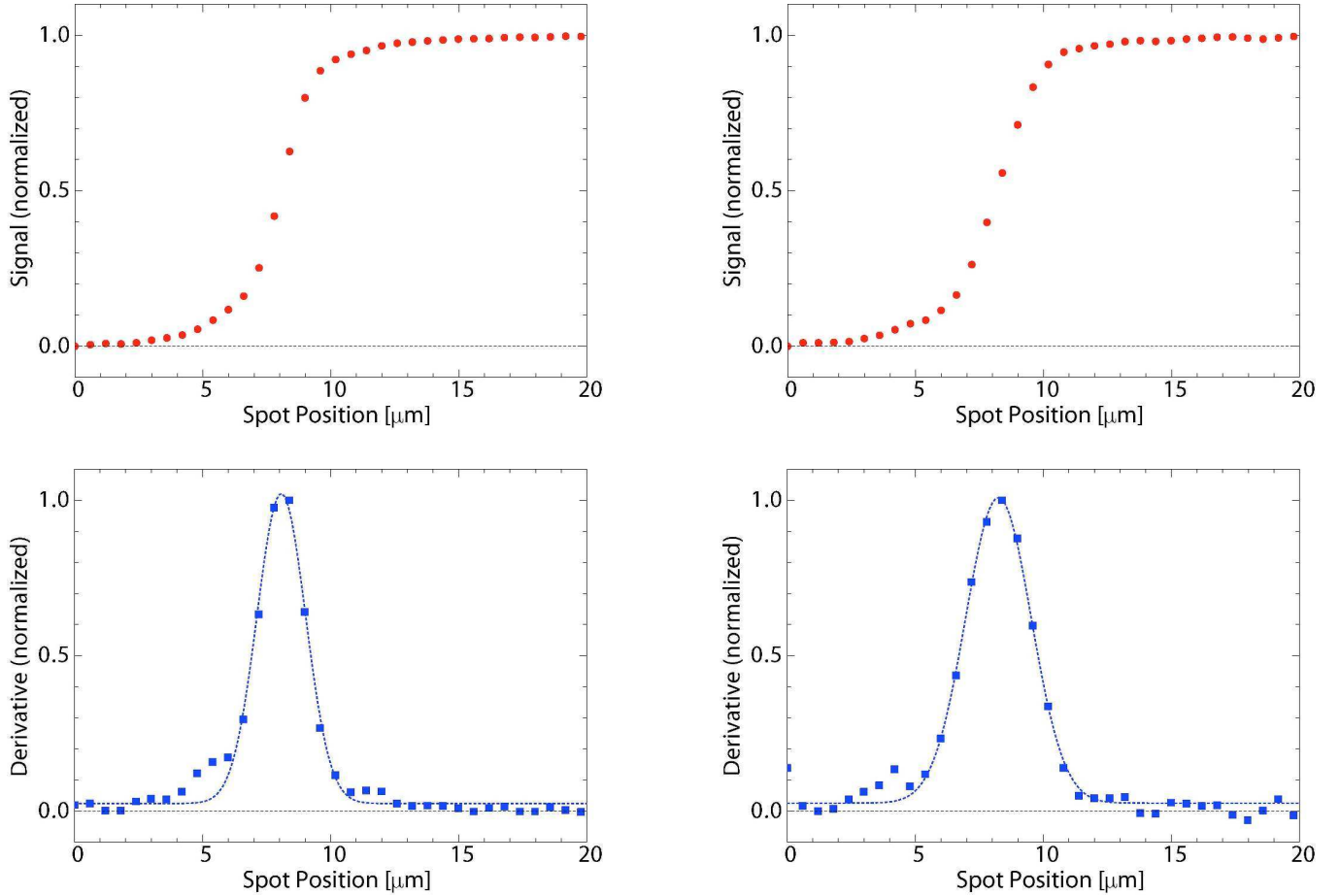


FIG. 3.— Knife-edge scans at a wavelength of 1050 nm (left panel) and at 1550 nm (right panel). The two top panels show the measured beam intensity as a function of the spot position. The two bottom panels show the corresponding derivatives. Fitting a Gaussian function to the bottom plots (dotted curves) yields a spot size of $\sigma = 0.95 \pm 0.03 \mu\text{m}$ for the 1050 nm wavelength and $\sigma = 1.28 \pm 0.04 \mu\text{m}$ for the 1550 nm wavelength.

TABLE 1

FIVE $1.7 \mu\text{m}$ HgCdTe FPAs HAVE BEEN TESTED USING THE SPOT-O-MATIC. THE TOP THREE SENSORS IN THE TABLE HAVE MEASURED QUANTUM EFFICIENCIES (QE) OVER 80%, EQUIVALENT TO NEARLY 100% INTERNAL QUANTUM EFFICIENCY. THE BOTTOM TWO SENSORS HAVE LOWER QUANTUM EFFICIENCY AND EXHIBIT SUBSTANTIAL NON-UNIFORM INTRA-PIXEL RESPONSE.

NIR sensor	Manufacturer	Device ID	Measured QE	Substrate removed
InGaAs	RVS ^a	Virgo 1k	> 80%	no
HgCdTe	RVS	Virgo 598141	> 80%	partial
HgCdTe	Teledyne ^b	H2RG #102	> 80%	yes
HgCdTe	Teledyne	H2RG #40	50 – 70%	no
HgCdTe	Teledyne	H1RG-BA #25	20 – 30%	yes

^aRaytheon Vision System, Goleta, CA

^bTeledyne Scientific & Imaging (formerly Rockwell Science Center), Camarillo, CA

geted during processing. The first three devices, which include detectors made of HgCdTe as well as InGaAs, exhibit good intra-pixel response. Analysis of the two-dimensional summed response profiles shows that the integrated response is uniform to better than 2% in each of these detectors. All three devices have nearly 100% internal quantum efficiency after correcting for reflections at the detector surface. Sections 3.1 and 3.3 present more detailed results for one HgCdTe device from the

first three high quantum efficiency detectors.

The other two devices have much lower quantum efficiency. One of these devices (H1RG-BA #25) shows large random deviations (greater than 10%) in uniformity. The other (H2RG #40) exhibits a periodic structure in pixel response. Measurements of the intra-pixel structure in H2RG #40 are presented in Section 3.4, as this data is used in Section 4 to demonstrate the effects of abnormal pixel response on undersampled point source photometry.

3.1. Intra-Pixel Sensitivity Variations in One Dimension

To test for possible loss in sensitivity near pixel boundaries, the responses of several adjacent pixels are summed, as displayed in Fig. 6. This integrated response is then used to estimate total response variation as a function of the PSF centroid position.

The summed data in Fig. 6 has an rms fluctuation of 1.02%. This data shows that, at pixel boundaries, the signal is shared equally between the two adjacent pixels. This result is typical of all three high quantum efficiency detectors tested. The data further suggests that photoelectrons generated at pixel boundaries are collected with close to unit efficiency. This confirms that lateral charge diffusion or capacitive coupling (Brown et al. 2006; Moore et al. 2004), rather than inefficient charge

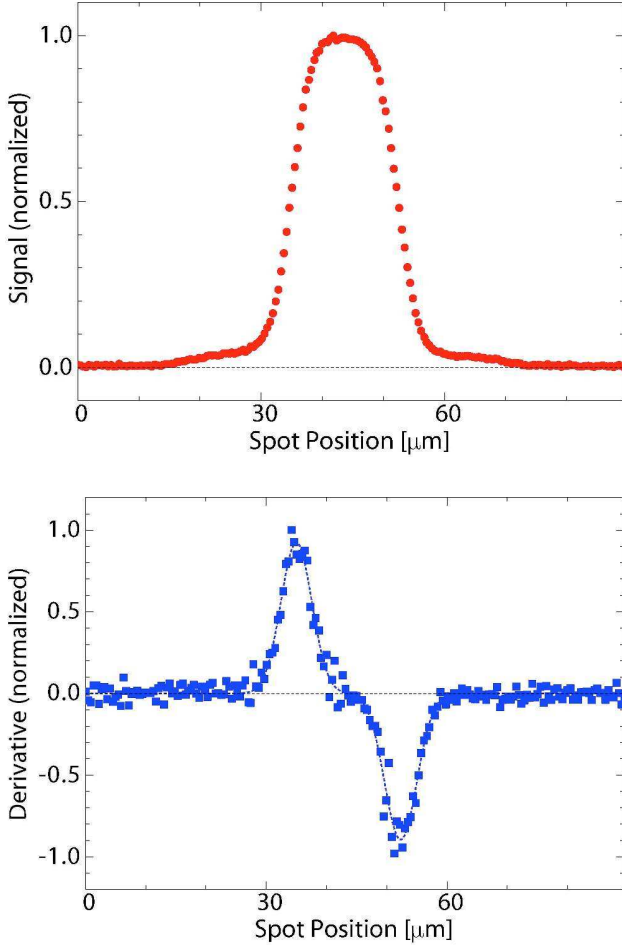


FIG. 4.— Top panel: One-dimensional scan of an arbitrary single pixel for 1050 nm light. Bottom panel: The derivative of the signal with best-fit Gaussian functions over-plotted (dotted curve). The average width (σ) of the two Gaussians is $2.6 \mu\text{m}$.

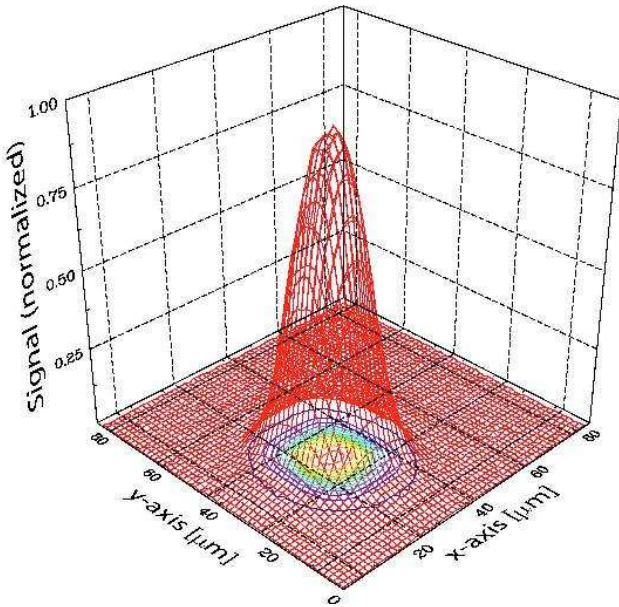


FIG. 5.— Two-dimensional scan of an arbitrary single pixel at a wavelength of 1050 nm. The grid on the bottom represents the physical size of the pixel.

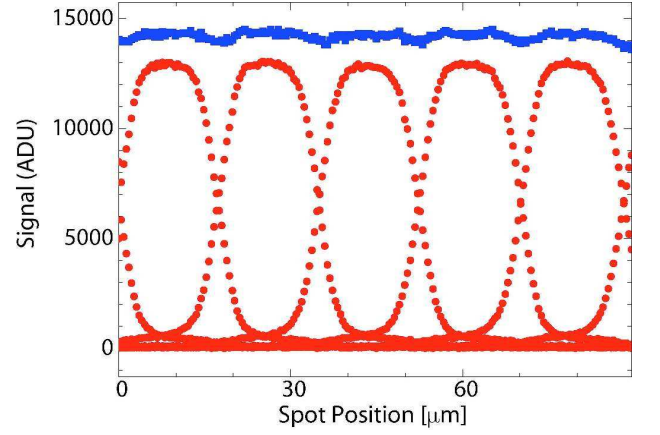


FIG. 6.— One-dimensional scan for 1050 nm light over five adjacent pixels located along the y direction. The scan is performed through the center of the five pixels. The response of each individual pixel (filled circles) is displayed along with the summed response (filled squares) of the five pixels. The rms fluctuation of the summed response from $20 \mu\text{m}$ to $70 \mu\text{m}$ is 1.02%.

collection, is the dominant source of the intra-pixel variation in this device. In addition, the tails in the PRF extend far into the neighboring pixel, a clear sign of capacitive charge sharing.

3.2. Extracting the Pixel Response

To determine the true pixel response function, the PSF must be unfolded from the raw data. This allows to understand how charge collection varies within a pixel, specifically how lateral charge diffusion and capacitive coupling affect the measured response.

Deconvolution of discretely-sampled data is often difficult due to the small magnitude of the high-frequency Fourier components. One common method used to ameliorate this problem is Wiener deconvolution, which adds a small noise term to each Fourier term. Wiener deconvolution was attempted to remove the Spot-o-Matic PSF from the PRF data with limited success. Consequently, an alternative method was employed which yielded more acceptable results. This method first approximates each component of the pixel response with a model response function. It then convolves these components and compares them to the raw data. Specifically, the detectors are modeled by convolving the measured Spot-o-Matic PSF with a boxcar response, diffusion, and capacitive coupling, respectively. The magnitude of the charge diffusion and capacitive coupling are then determined by fitting this model to the raw data.

The fitting procedure starts with a two parameter (width and position) boxcar response function⁹. The boxcar is first convolved with a Gaussian function with $\sigma = 0.95 \mu\text{m}$, as measured using the Foucault knife-edge scanning procedure. The result is then convolved with a diffusion term proportional to the hyperbolic secant, given as

$$I_D(\Delta x) \propto \text{sech}(\Delta x/l_d), \quad (2)$$

where l_d is the diffusion length and Δx is the distance of the collected charge from the location of the electron-hole

⁹ The width was fixed at the detector pixel pitch ($18 \mu\text{m}$), however, allowing this parameter to vary during the fitting procedure showed no significant impact on either the best fit value for the diffusion or the capacitive coupling.

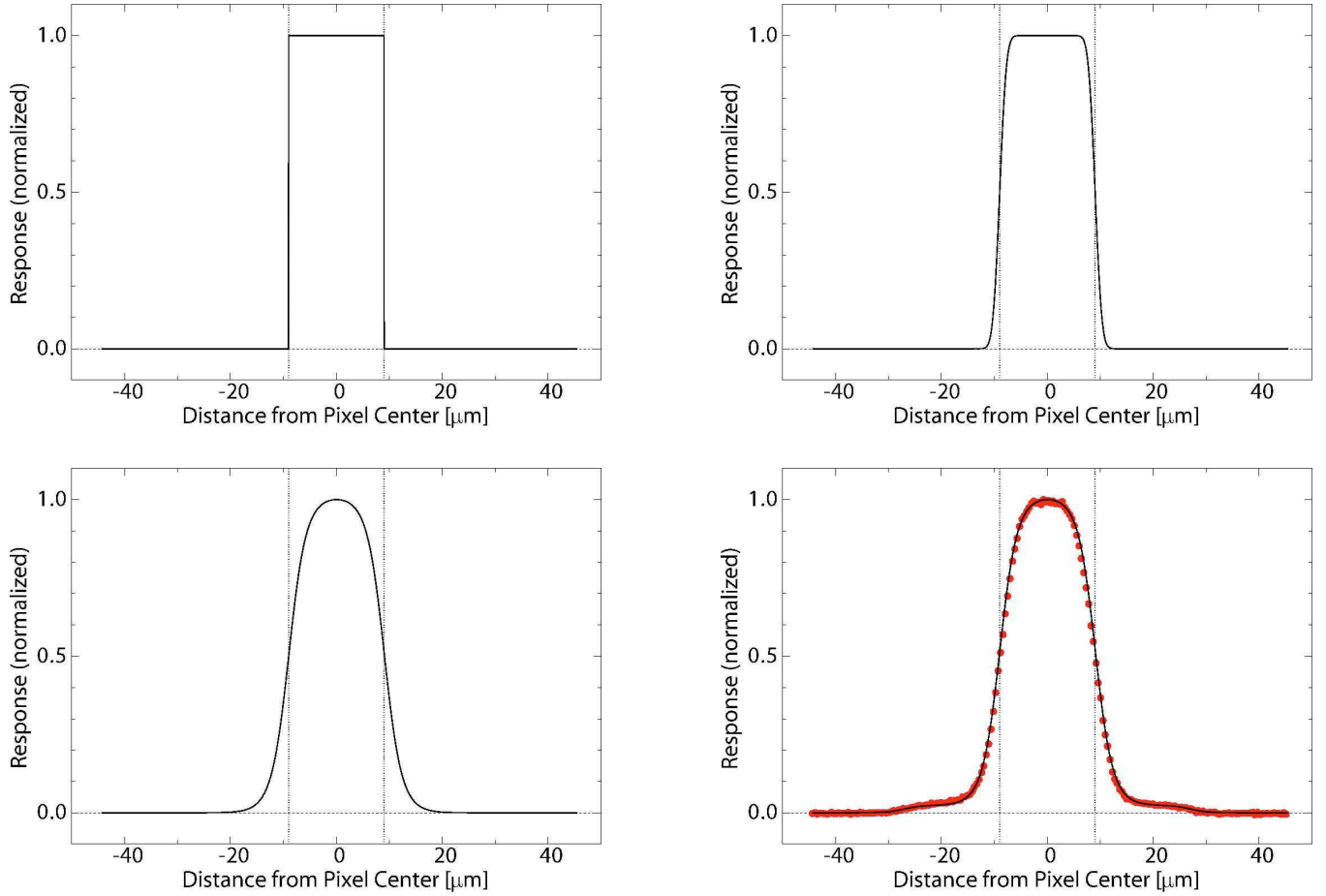


FIG. 7.— Convolution of one-dimensional pixel scan data. The procedure begins with a boxcar PRF (top left), then adds the Spot-o-Matic PSF (top right), lateral charge diffusion (bottom left) and finally capacitive coupling (bottom right). The dotted line represents the physical pixel boundary. The raw data is added in the bottom right panel.

pair. Finally, capacitive coupling is added to the model by assuming a grid of identical pixels with a coupling coefficient α . In this case, each pixel gains or loses a charge of α times the difference between the pixel's value and that of each of its four neighbors. Figure 7 shows the progression of the model function from the initial boxcar response to the measured pixel response, using the best fit parameters.

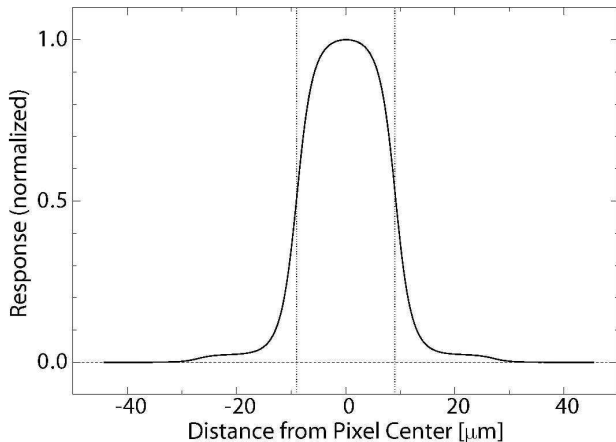


FIG. 8.— A boxcar response convolved with the best fit diffusion and capacitive coupling components. This is the pixel response function with the effects of the Spot-o-Matic PSF removed.

The extracted pixel response is shown in Fig. 8. Note that the pixel response includes only diffusion and capacitive coupling convolved with a boxcar response function. The best fit to the raw one-dimensional scan data, which also includes the Spot-o-Matic PSF, is shown in the bottom right panel of Fig. 7. The pixel responses with and without the spot PSF included are nearly indistinguishable from each other. The impact of the PSF is minimal when σ is much less than the diffusion length l_d . For the pixel shown, the best fit values for diffusion length and capacitive coupling are $l_d = 1.87 \pm 0.02 \mu\text{m}$ and $\alpha = 2.1 \pm 0.1 \%$, respectively. From an independent measurement of the capacitive coupling using the autocorrelation function, a coupling coefficient of $2.2 \pm 0.1 \%$ (Brown et al. 2006) was obtained, a value which is in excellent agreement with the Spot-o-Matic results.

3.3. Intra-Pixel Sensitivity Variations in Two Dimensions

The two-dimensional scans from the Spot-o-Matic produce a wealth of information about both pixel structure and device performance. Figure 9 shows a two-dimensional scan extended over an array of 4×4 pixels. In order to include all the charge collected across this array, a 8×8 array of pixels is summed to produce this spectrum. The fluctuations in the summed spectrum

have an rms deviation of 1.9%. Approximately 1% of the fluctuations in the summed spectrum are statistical, due to the large thermal background created by the warm optics radiating through the dewar window. Subtracting this noise in quadrature, the intra-pixel sensitivity variations are 1.6%. When this detector response is convolved with a critically sampled PSF¹⁰, variations of this magnitude have no measurable effect on precision photometry (see Section 4).

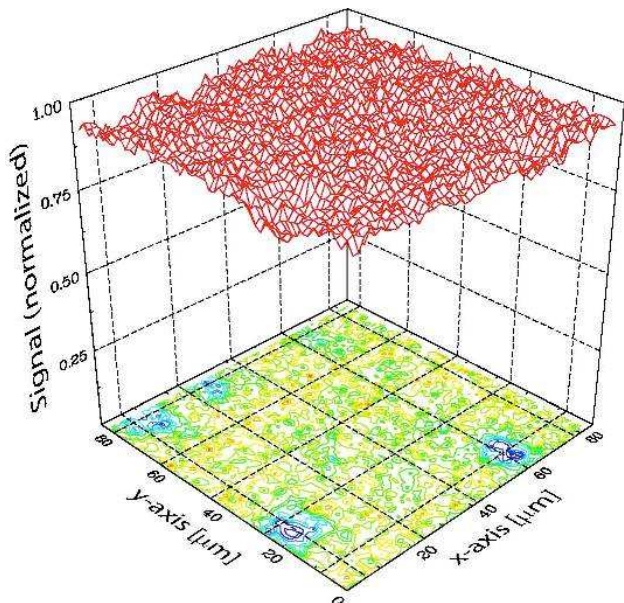


FIG. 9.— Two-dimensional scan at 1050 nm wavelength, summed over an array of 8×8 adjacent pixels. Only the response of the inner 4×4 array is shown.

The noise can be reduced by averaging the response over many exposures at each position. However, this procedure is not necessary here, as the statistical uncertainty limit of 1% is sufficient to achieve the goals of the measurement. The statistical fluctuations quickly average out when convolving the two-dimensional response functions with larger point spread functions.

Figure 9 shows a two-dimensional scan for a wavelength of 1050 nm. The four small dark patches in the contours in Fig. 9 correspond to a drop in sensitivity of approximately 5%. These dips in sensitivity could be due to small dust particles on the detector surface or defects in the HgCdTe which lead to traps or recombination. The same dips in sensitivity are reproduced in scans using a 1550 nm wavelength (not shown). These small dips are not apparent in flat-field images and do not impact the photometric precision. However, they do show that the Spot-o-Matic can detect micron-sized variations at the percent level. They also demonstrate that a simple addition of adjacent pixels restores photometric precision to better than 2%, despite these dips in sensitivity.

3.4. A sensor with anomalous substructure

All of the high quantum efficiency detectors have uniform pixel response and small ($< 2\%$ rms) deviations

¹⁰ Critical sampling is defined as a PSF size (FWHM) equal to two resolution elements (e.g. pixels).

in the summed spectrum. Detectors with low quantum efficiency were expected to exhibit large random fluctuations (as in H1RG-BA # 25) or dips in sensitivity near pixel edges, as observed by Finger et al. (Finger et al. 2006). An unexpected result was discovered in an early engineering grade device, H2RG # 40, which shows an anomalous intra-pixel structure. This detector displayed close to the best performance for a $1.7 \mu\text{m}$ HgCdTe detector at the time it was fabricated. The read noise (35 electrons using Fowler-1), quantum efficiency (50 – 70%) and dark current (0.05 electrons/pixel/second) were typical of the best performance achieved in developmental FPAs for the *Hubble Space Telescope's* Wide Field Camera 3 upgrade (Robberto et al. 2004), but none of these tests indicated any potential problems with the pixel response.

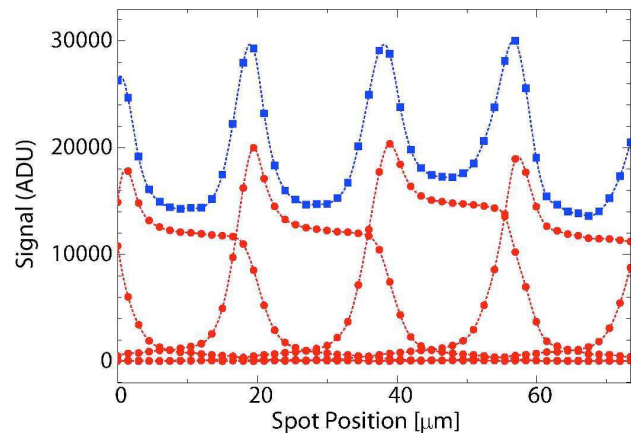


FIG. 10.— One-dimensional scan over four adjacent pixels located along the y direction. The scan is performed through the center of the four pixels. The response of each individual pixel (filled circles) is displayed, together with the summed response (filled squares) of the four pixels.

One-dimensional scans of this device showed an unexpected asymmetric intra-pixel response (see Fig. 10). The two-dimensional profile of an individual pixel in Fig. 11 revealed this puzzling “chair-like” structure in greater detail. This same structure is present in all the pixels tested on this detector. Three distinct regions, including two near the edge and one near the center of the detector, were sampled with the Spot-o-Matic and all exhibit a similar intra-pixel response.

The summed response of this device exhibits the periodic peaks and valleys shown in Fig. 12. The rms variation in the summed spectrum is 18%. Since measurements of typical device characteristics average out any intra-pixel variations, these measurements would not capture the anomalous substructure revealed by the Spot-o-Matic measurement. Yet such intra-pixel sensitivity variations can significantly degrade photometry in undersampled observations, and thus are important to detect.

4. PHOTOMETRY SIMULATIONS

The single pixel response functions and two-dimensional summed scans produced with the Spot-o-Matic can be used to simulate photometry errors for a range of different PSF widths. For critically or oversampled point spread functions, intra-pixel variations have

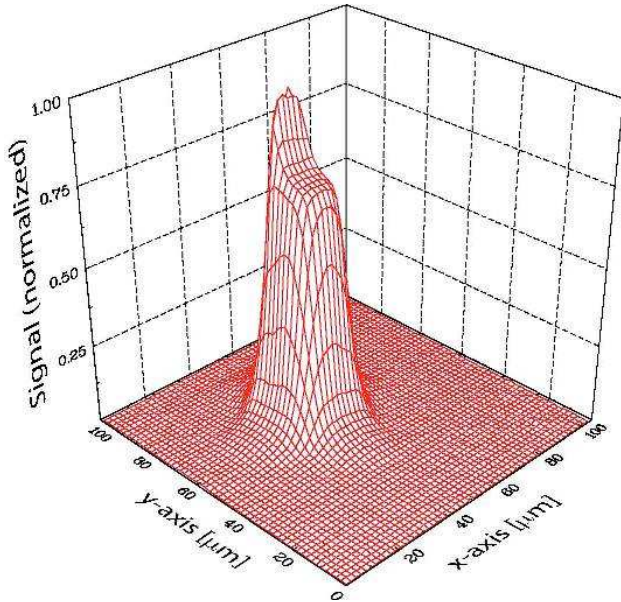


FIG. 11.— Two-dimensional scan of an arbitrary single pixel at a wavelength of 1300 nm for H2RG #40.

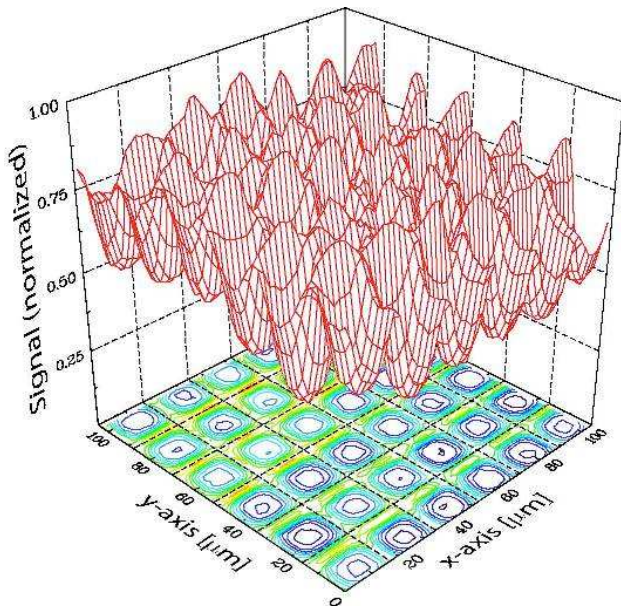


FIG. 12.— Two-dimensional scan summed over a 6×6 array of adjacent pixels for H2RG #40.

little impact on photometry. However, for undersampled images, sensitivity variations (such as those observed in FPA H2RG #40) can lead to large photometry errors. Assuming modest undersampling (e.g. a factor of three), the intra-pixel variation in this particular device would result in rms photometry errors of about 5%.

Figure 13 shows the fractional rms error as a function of PSF size for the two detectors profiled in Section 3. The results shown in this figure assume a grid of identical pixels with the two-dimensional response profiles shown in Figs. 5 and 11. The summed response spectrum of the pixel grid is convolved with a Gaussian point spread

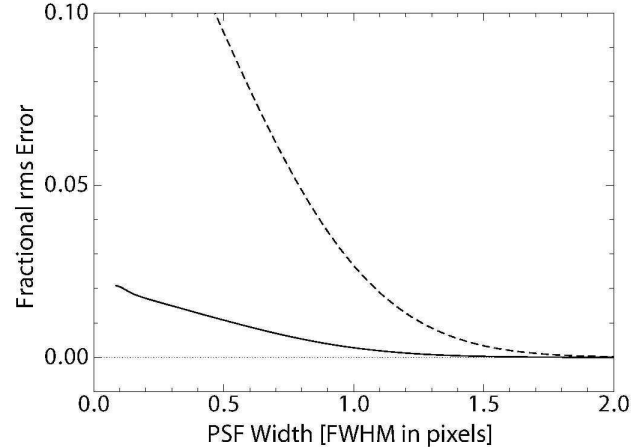


FIG. 13.— Fractional photometric error vs. PSF size for a typical high quantum efficiency detector (solid curve), and FPA #40, with 50% to 70% quantum efficiency and an anomalous substructure in the pixel response (dashed curve).

function with FWHM values ranging from a fraction of a pixel to two pixels. For the three high quantum efficiency detectors tested, the photometric errors are less than 2% for any size PSF. However, if a detector has a substructure as displayed in Fig. 12, the photometric errors may be well over 10% when the PSF size is much less than one pixel. As the PSF size increases, the intra-pixel variations average out, and for a PSF size of more than two pixels the photometric errors are negligible.

5. SUMMARY

The automated point projection system described here provides the ability to detect and accurately characterize substructure in the pixel response of focal plane detectors. While the measurements were limited to NIR detector arrays, the Spot-o-Matic can also be used for the measurement of sub-pixel structure in CCDs.

The Spot-o-Matic has been tested with five detectors from both Raytheon Vision Systems and Teledyne Scientific & Imaging. The results for devices with near 100% internal quantum efficiency indicate that the pixel response is uniform to better than 2% in all areas tested. This result is not surprising; high quantum efficiency detectors must count nearly all of the incident photons.

By contrast, a detector with moderate quantum efficiency, and reasonable read noise and dark current levels has exhibited a strong asymmetric intra-pixel structure. This otherwise high quality detector would cause large photometric errors in an undersampled instrument. Spot-o-Matic measurements can discover and characterize variations of this nature. For undersampled imaging such a detailed understanding of the intra-pixel structure is essential for obtaining precise photometric measurements.

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